

Occupancy measurement in commercial office buildings for demand-driven control applications—A survey and detection system evaluation



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ABSTRACT

Commercial office buildings represent the largest in floor area in most developed countries and utilize substantial amount of energy in the provision of building services to satisfy occupants' comfort needs. This makes office buildings a target for occupant-driven demand control measures, which have been demonstrated as having huge potential to improve energy efficiency. The application of occupant-driven demand control measures in buildings, most especially in the control of thermal, visual and indoor air quality providing systems, which account for over 30% of the energy consumed in a typical office building is however hampered due to the lack of comprehensive fine-grained occupancy information. Given that comprehensive fine-grained occupancy information improves the performance of demand-driven measures, this paper presents a review of common existing systems utilized in buildings for occupancy detection. Furthermore, experimental results from the performance evaluation of chair sensors in an office building for providing fine-grained occupancy information for demand-driven control applications are presented.

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1. Introduction

1.1. Building energy consumption

The built environment is currently a major consumer of non-renewable fossil energy, accounting for more than one-third of the total final energy consumed in both OECD (Organization for Economic Cooperation and Development) and non-OECD countries [1–4]. Due to continued economic and population growth in OECD and non-OECD countries respectively, it is anticipated that the built environment in the near decade would be the main energy consuming sector [3]. Within the built environment, commercial office buildings are the largest in floor space and energy use in most countries [5]. In the Netherlands for instance, it is estimated that there are around 78,000 office buildings and the energy use per square meter is almost double that of households [2]. Overall, both the electricity use and gas consumption of buildings are increasing slightly, despite targets set by various governments, which anticipates 20% reduction in energy use by the year 2020 [6,7].

In commercial office buildings, lighting, heating, ventilation and air-conditioning systems (L-HVAC) are the main energy consumers, together accounting for about 70% of the total energy consumed in a typical office building [4–9]. Over the years, numerous occupancy detection systems have been developed for use in demand-driven control of lighting systems [10], but limited occupancy detection tools with comprehensive fine-grained information have been developed and available for use in demand-driven control of HVAC systems.

1.2. Energy consumption of ventilation systems

In large commercial office buildings, air circulation is commonly carried out using either a constant air volume (CAV) or a variable air volume (VAV) ventilation systems or a hybrid combination of both systems. CAV systems have been in use since the very first introduction of large-scale commercial air-conditioning systems, while VAV systems gained wide use in the early 1960s [11,12]. As the name implies, CAV systems supply a constant air volume through the space requiring ventilation while also heating, cooling, humidifying or dehumidifying the air to meet the comfort demands of occupants. On the other hand, VAV systems vary the supply airflow rate continuously in adaptation to the heating and cooling load, as well as space occupancy. In both systems, the main energy consuming components are (1) cooling and heating of air by air handling units (AHUs) E_A ; (2) heating of air by VAV boxes E_V ; (3) air humidification or dehumidification E_H and (4) air circulation by fan units E_F [13–17].

In the design and operation of net-zero and energy efficient buildings, the control objective is usually ensuring that the total energy E_T , consumed by the HVAC system is kept at the minimum possible value that satisfies the required comfort conditions, i.e., $\text{Min. } E_T = [E_A + E_V + E_H + E_F]$. Therefore in achieving the minimum

value of E_T without compromising on comfort, a number of demand driven control strategies such as optimal start/stop, fan pressure optimization, supply-air-temperature reset and ventilation optimization, are often commonly employed by control engineers in the design and operation of HVAC systems [13,18–20].

1.3. Occupant driven control

A building occupant, totally unaware of the need to consciously conserve energy, can increase a building's energy use by up to one-third of its design performance, while an energy-conscious user behaviour can provide worthwhile savings of up to the same amount [5]. Occupants cannot however be completely trusted to exercise energy conscious behaviour, particularly in large commercial buildings where they are not directly responsible for the cost implication. To this end, demand-driven controls which are measures aimed at improving the energy efficiency and performance of building systems using fine-grained building load information for control of building systems such as demand controlled ventilation (DCV) and demand control of lighting systems, are often relied on. Demand-driven control is one of the main components of energy demand side management (DSM), which is a key component of the smart Grid [21,22].

In a typical large office building, it is not uncommon to find spaces partially occupied or even unoccupied for significant periods during the course of a typical business day [23–25]. Fine-grained information about building occupancy can thus lead to improved delivery of lighting, heating, ventilation and air conditioning as well as improved utilization of space [7,27,28]. Using fine-grained information of building occupants, demand-driven control measures have been demonstrated by a number of authors [10,16,28] to provide reduction in energy utilized by both lighting and HVAC systems for the provision of acceptable user comfort conditions.

Theoretically, a plethora of literature agree on the energy efficiency improvement and energy reduction potential of HVAC systems that operationally take into account fine-grained occupancy information [5,14,16,25,26]. Comprehensive fine-grained building occupancy information is however difficult to obtain because it varies dynamically through the course of the day in relation to space function, occupant function and behaviour. It is therefore not uncommon to discover that a substantial number of commercial buildings still make use of coarse grained occupancy information, assumed occupancy profiles and schedules with little or no consideration at all of the energy implications and savings accruable at periods when spaces are partially occupied or unused [8,14,25].

1.4. Contribution of this paper

In the application of occupant-driven demand control measures in buildings, particularly the control of slow responding systems such as HVAC systems, there are very limited tools available with

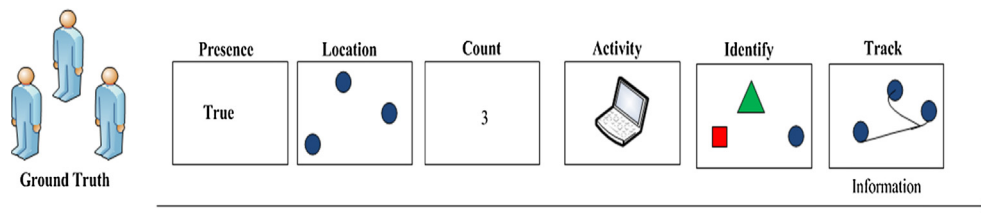


Fig. 1. Spatial-temporal properties of occupancy measurement.

the ability to provide the needed comprehensive fine-grained occupancy information required to optimize system performance. Where available, their application in practical building operation is hampered by a number of drawbacks. This paper enumerates on the drawbacks of common available detection systems and provides details as well as results of an experimental set-up to evaluate the performance of low-cost chair sensors with the ability to provide fine-grained occupancy information.

The subsequent sections of this paper are laid-out as follows: Section 2 provides a description of the components of comprehensive fine-grained occupancy information. The section also provides a review of common existing occupancy measurement systems, highlighting the strengths and drawbacks of each system. Section 3 provides details of the designed chair sensor as well as details of the experimental set-up. In Section 4, the performance, potentials, as well as the limitations of the system are presented while Section 5 presents the study's conclusions as well as future work.

2. Occupancy information and measurement

2.1. Occupancy information

Comprehensive, fine-grained occupancy information can be described using six spatial-temporal properties [27,28] depicted in Fig. 1 and arranged in order of significance as it relates to building energy consumption.

- **Presence**—Is there at least a person present?—This property provides information about 'when' occupants are present in a particular room or thermal zone. User presence in a space, as depicted in Fig. 2 is often modelled using diversity factors [29]. Using diversity factors, daily profiles of presence can be created and combined to make up a representative week of presence.
- **Location**—With information on presence available to the L-HVAC system, it is as well crucial that information on 'where' a person is present be available. This property relates to occupants 'coordinates' within the building or the particular thermal zone in which occupants are situated. This property is important giving

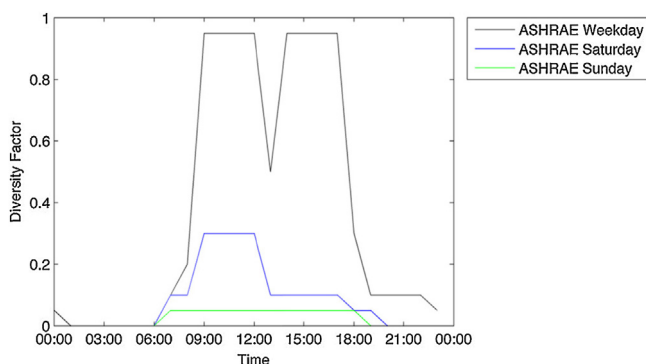


Fig. 2. ASHRAE recommended occupancy diversity factor by day type for an office building (Duarte et al. [29]).

that majority of commercial office buildings are often composed of more than one thermal zones [14].

- **Count**—How many people are present?—This property provides information on the 'numbers' of occupants in a particular thermal zone within the building. Information on count makes it feasible to tailor the operation of cooling, heating and ventilation systems to actual building occupancy [13,14].
- **Activity**—What is the person doing?—This property provides information on 'what' activity is being carried out by occupants in a space. Each activity as depicted in Fig. 3, results in a different body metabolic rate and CO₂ production [30]. Body metabolism rate is one of the parameters required in the determination of the predicted mean vote (PMV) value [31], which is a commonly used model in the evaluation of acceptable indoor thermal environment. Information on user activity can hence be used in the provision of satisfactory indoor environment for building occupants.
- **Identity**—Who is the person?—This property relates to information on 'who' is in a particular thermal zone or space in the building. Though commonly used in security applications, but there is a new paradigm shift in thermal comfort research towards the development of personalized thermal comfort systems [31,32]. Information on occupants identity can be harnessed and used to provide user preferred personalized comfort conditions.
- **Track**—Where was this person before?—This property provides information about the particular occupant's movement history across different thermal zones in the building. This property is essential in the design of proactive comfort systems [14,25].

The six properties described above provide insight into what constitutes comprehensive, fine-grained occupancy information. The next section provides a survey of the common occupancy detection systems typically used in office buildings for demand-driven applications and evaluates each against the properties described above.

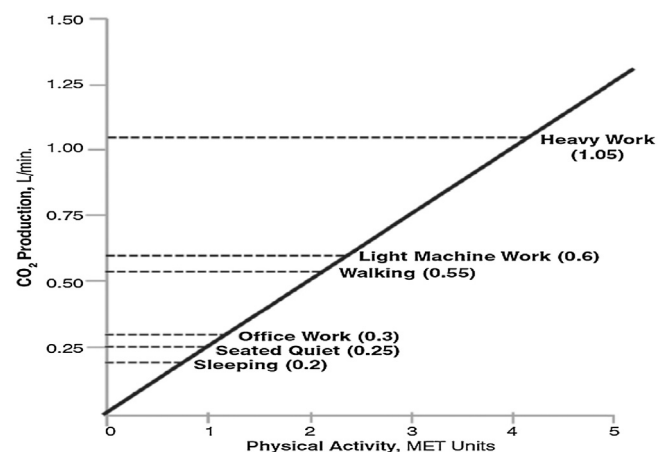


Fig. 3. CO₂ production and metabolic activity (Dougan and Damiano [30]).

Table 1
Classification of occupancy detection systems.

Sensors	Method		Function		Infrastructure	
	Terminal	Non-terminal	Individualized	Non-Individualized	Implicit	Explicit
CO ₂ sensors	×	✓	×	✓	×	✓
PIR sensors	×	✓	×	✓	×	✓
Ultrasonic sensors	×	✓	×	✓	×	✓
Image sensors	×	✓	×	✓	✓	✓
Sound sensors	×	✓	×	✓	×	✓
EM Signals	✓	×	×	✓	✓	✓
Power meters	×	✓	×	✓	×	✓
Computer App.	×	✓	×	✓	✓	×
Sensor fusion	✓	✓	✓	✓	✓	✓
	Location	Presence	Count	Activity	Identity	Track
CO ₂ sensors	✓	✓	✓	✓	×	×
PIR sensors	✓	✓	×	×	×	×
Ultrasonic sensors	✓	✓	×	×	×	×
Image sensors	✓	✓	✓	✓	✓	✓
Sound sensors	✓	✓	×	×	×	×
EM signals	✓	✓	✓	✓	✓	✓
Power meters	✓	✓	×	✓	×	×
Computer App.	✓	✓	✓	✓	✓	×
Sensor fusion	✓	✓	✓	✓	✓	✓

2.2. Occupancy measurement systems

In general, occupancy detection systems commonly found in commercial office buildings for obtaining the spatial–temporal properties described above can be grouped as shown in Table 1 based on

- Method**—Occupancy detection systems can be classified according to the need for a terminal [33] such as a mobile phone [34,35] or radio frequency identification tag (RFID) [15,35] that should be carried by the building user. Non-terminal based detection systems on the other hand such as passive infra-red (PIR) sensors, carbon-dioxide (CO₂) sensors provide occupancy information without the need for building users to carry any device.
- Function**—In recent research on thermal comfort in buildings [31,32], personalized comfort systems, which have been shown to provide reduction in the energy required for providing user preferred thermal conditions are at an advanced stage in their development. Towards this direction, occupancy detection systems can also be categorized based on their ability to detect, identify and track individual building occupants. Detection systems with these capabilities are termed individualized systems, while systems with only the ability to provide aggregate occupancy without knowledge of user identities or exact coordinates in the building are termed non-individualized systems [14].
- Infrastructure**—Occupancy detection categorization based on infrastructure refers to the distinction between detection systems installed for the sole purpose of measuring building occupancy and those systems which provide building occupancy information as a secondary function [8,27]. CO₂ and PIR sensors are used in buildings to provide occupancy information (*explicit systems*), while on the other hand occupancy information can also be inferred from the use pattern of building appliances such as computers, printers and other similar office appliances (*implicit systems*).

2.2.1. CO₂ based detection systems

Humans naturally exhale CO₂ on a constant basis making it present in varying amount in spaces. The measurement of the amount of CO₂ in a space can hence be employed in determining occupancy information on presence [36,37], location [36,37], count [38,39] as well as user activity [16,30]. CO₂ sensors measure the

concentration of gases in a space in parts-per-million (PPM). It is a commonly used tool for the measurement of occupancy in buildings for demand-driven control of HVAC systems because it is non-terminal based, can provide an estimate of count as well as its ability to provide information on the indoor air quality [36–41], which is also linked to productivity [42]. The authors in [37] demonstrated the use of CO₂ based occupancy detection for demand controlled ventilation in an office building using two different control strategies. The first strategy uses the carbon dioxide concentration in the ventilation return duct as an indicator of occupancy density and adjusts the outdoor air based on this. The second strategy maintains the CO₂ concentration at the ventilation supply point at a set-point value determined using the monitored zone airflow rates and with the assumption that full occupancy occurs. However, both strategies at times result in over ventilation or under ventilation, which impacts both user comfort and energy.

CO₂ occupancy detection systems as shown in Table 1 are non-individualized explicit occupancy detection systems. But the sensor's use in building controls is still however hampered due to a number of drawbacks including: (a) Varying and slow gas mixture rate—the operation of the sensor is greatly influenced by external conditions such as variations in wind speed, intermittent opening and closing of doors and sensor location, and pressure difference [43], (b) the measurement of count, which is crucial in tailored delivery of ventilation in spaces using demand-controlled ventilation, is based on estimates [14,44]. The authors in [38] developed a relation for determining the number of occupants in a space using CO₂ concentration measurements, though some of the parameters used were actual measured values the others were approximate values which tend to vary in a dynamic environment.

2.2.2. Passive infrared detection systems (PIR)

All objects including humans with a temperature above absolute zero emit heat energy in the form of radiation. The emitted infrared radiation is invisible to the human eye but can be detected by electronic devices such as PIR sensors, which are designed specifically for such purpose. In principle, PIR sensors detect the energy given off by objects within its view [44,45]. The sensor is passive as it does not emit any energy itself, but sends out a signal whenever there is a change in the infrared energy in a sensed environment. Based on the afore-mentioned operational principle as well as ease of operation, they are one of the commonly used occupancy detection system commercially available for demand driven control applications in

buildings particularly in the control of lighting systems [45]. The authors in [10] provided a breakdown of the accruable energy savings possible from empirical field studies on the use of PIR sensors in offices as well as spaces that are not frequently used and showed that energy savings upward of 10% are achievable.

PIR sensors are also non-individualized, non-terminal based explicit detection systems, and have been demonstrated to provide fine-grained occupancy information on user presence [8] and location [33]. Their application in buildings is however somewhat limited to occupant driven control of lighting systems due to a number of reasons: (a) the sensors output is binary [14,45] making it impossible to provide information on count, which is an essential property required for demand controlled ventilation; (b) PIR sensors require a direct line of sight between the sensor and occupants in a space and requires continuous motion to function effectively. In other words, when occupants are seating still or the sensors view is impeded by other objects the sensor registers a false off state [28]. This effect often fuel user dissatisfaction as the system becomes a nuisance to the user since they are compelled to make gestures in order to get the controlled system back on [43] and (c) Studies have also demonstrated the sensors can be triggered by heat currents from HVAC systems, thus causing the sensors to register a false ON state at times even when spaces are unoccupied [14].

2.2.3. Ultrasonic detection systems

Ultrasonic sensors were introduced for demand-driven applications as an improvement over PIR sensors as they do not require line of sight and continuous movement. Unlike PIR sensors which are passive, ultrasonic sensors are active devices which emit and receive ultrasonic sound waves to and from the environment [45]. The sensors are ideally, non-terminally-based and non-individualized, but can be implemented as terminal-based and individualized detection system for other specialized applications [34,46]. Ultrasonic sensors have also been demonstrated to have the capacity to provide occupancy information on location and presence [10]. The authors in [47] demonstrated that ultrasonic sensors are able to provide user presence and location information through changes in the echo intensity of the transmitted signal. Its use in demand-driven control of HVAC systems is also limited due to a number of drawbacks: (a) The sensor's output is binary, hence its inability to provide information on count. (b) The system is susceptible to false ONs often triggered by vibrations such as the air turbulence from HVAC systems, or even moving paper coming from a printer [45].

2.2.4. Image detection systems

Image recording devices such as video cameras are often used in buildings for security purposes, though implicit building systems, their use has also been explored for occupancy measurement in buildings [48–50]. Image detection systems are non-terminal based and can be used to provide individualized functions. They have been demonstrated to have the capability to provide occupancy information on location, count, activity, identity and track [48,50]. OPTNet a wireless network of multiple imaging devices was developed by the authors in [48] to determine occupancy in the various thermal zones of a building. The authors demonstrated from the test building that energy saving upwards of 20% was achievable. The application of image detection system in large-scale commercial demand-driven control of comfort systems in buildings is however still at an early stage of development and is rarely used for a number of reasons ranging from (a) Image detection systems require line of sight hence requiring placement of the camera at locations with minimal or less obstructions [49]; (b) Advanced signal processing and expensive explicit hardware is required by the system to be able to provide information on presence, count, identity and activity [8]. The authors in [48] reported the deployment,

testing, verifying the performance of the system was extremely difficult and (c) User privacy is still also a major source of concern [14].

2.2.5. Sound detection systems

The measurement of sound waves in a space is another phenomenon that is currently been studied for use in occupancy driven control application in buildings [51]. As building occupants often produce a variety of audible sound waves, its measurement using microphones can provide occupancy information on location and presence. Sound detection systems are non-terminal, explicit detection systems, which can be used for only non-individualized functions. The authors in [51] developed a prototype system consisting of 8 microphones and running an occupancy detection algorithm to determine the number of people in a space. The developed system as part of a much broader project shows great potential in determining occupancy information in buildings. However the use of sound detection systems is seldom used for standalone heterogenous occupancy detection in building due to drawbacks such as (a) sound waves from non-human sources in buildings can trigger the sensors, (b) the sensors registers false off when spaces are occupied and no sound is made.

2.2.6. Electromagnetic signal (EM) detection systems

Electromagnetic signals (EM) present in the form of wireless fidelity (WIFI), Bluetooth, radio frequency identification tags (RFID) enabled devices are systems also commonly found in commercial office buildings. Occupancy detection based on the measurement of EM signals are often terminal based and provide individualized functions [14]. The system is usually composed of a transmitting (usually carried by the user) and a receiving node (usually static), which allows for either the measurement of the energy or timing of the response echo of a transmitted signal by the receiving node [52]. The transmitted signal may consist of short series of pulses or a modulated radio signal. The system can be implemented as both an explicit detection system [34] or as an implicit system [35].

Occupancy detection systems based on the measurement of EM signals have been demonstrated to have the ability to provide occupancy information on user location, presence, count, identity and track [14,35]. The authors in [34] presented performance evaluation results of three different technologies for indoor localization, which can also be integrated in building systems for demand driven control of building systems. The evaluated systems showed varying degrees of accuracy as well as varying implementation cost, ease of installation and maintenance. Though having the capability to provide comprehensive fine-grained occupancy information for demand driven applications in buildings, their use is limited as a result of (a) Privacy-being terminal based, users feel they are constantly been monitored. (b) Connection or association of multiple connected devices to one occupant. Building users often have more than one device enabled with EM signals that can be detected, which can result in false registration of presence, location and count [27,35]. (c) Often the terminal device held by the user is usually battery power and not sustainable for long-term data acquisition. In addition a complex and advanced signal processing station is often required [27,34].

2.2.7. Energy measurement based detection devices

With increased awareness on energy conservation, portable devices that measure the energy consumption of appliances for visualization of energy use are now commercially available and being explored for use as well in demand driven applications in buildings [53,54,55]. Power meters are at times installed on vital building appliances such as printers and personal computers. The change in energy consumption when the device changes state from idle to active provides information from which users location and

presence could be inferred. The authors in [54] demonstrated this potential and showed that energy expended on fast-responding building systems could be reduced by up to 50%. It was also observed that for the test building, users spent an average of 75.8% of the work day in the office space, hence revealing energy saving can be achieved by reducing the energy consumption of comfort systems and plug loads for the over 20% period occupants were not present in the work space. Though implicit systems, they are non-terminal based and cannot be used for individualized functions. The main drawback of the system is the coarse-grained nature of the inferred information as such they are often used in combination with multiple sensors to improve their performance [53,56].

2.2.8. Computer activity detection systems

Personal computers are implicit building appliances and as building occupants often spend significant amount of time on them [57,58] it's a source from which occupancy information can be deduced [8,27]. In [59], the authors demonstrated the potential of using keyboard and mouse activity sensors in an office building for occupancy detection as well as for user activity detection. The authors in [8] and [27] also demonstrated its use for determining user presence in a buildings. The aggregated output can also be used to obtain coarse grained occupancy information on count. Though a low-cost means of obtaining occupancy information in buildings, its use is still limited due to (a) user privacy and computer data security, (b) false ON, when occupants are present and not making use of a personal computer.

2.2.9. Sensor fusion

To overcome the drawback of individual detection system, a fusion of multiple sensors is often encouraged for use in occupancy detection for demand-driven applications [45,60]. The resulting detection system benefits from the key strength of each individual system that makes up the fused system, while playing down effects the drawback individual sensors might have on the system.

The authors in [15] used a PIR sensor in combination with a magnetic door reed switch to determine presence in a cell office within a building. Also in addition to the wireless network of multiple cameras developed by the authors in [48], a wireless network of PIR sensors was as well developed to improve the overall performance of the detection system. Similarly, the authors in [59] utilized a combination of sound sensors, pressure sensors as well as keyboard and mouse sensors to determine user presence, location, count, activity and identity in order to improve building energy consumption. Though the system out-performs all previously considered occupancy detection systems in providing occupancy information for demand-driven control applications in buildings due to its non-heterogeneous nature, it does often require additional explicit infrastructure and advanced data processing which is often costly [8].

3. Experimental evaluation of chair sensors in buildings for occupancy measurement

In the preceding section, occupancy measurement systems commonly used in commercial office buildings for demand-driven control applications such as the control of lighting and HVAC systems were discussed and the drawbacks and strengths of each system enumerated on. This section introduces chair sensors and evaluates their performance in buildings for demand-driven control applications, particularly focusing on the system's ability to provide information on presence, location and count. The sensors performance was evaluated against the performance of CO₂ sensors, which are commonly available and used in buildings for demand-driven control of HVAC systems because they have the ability to provide an estimate of space occupancy.



Fig. 4. Cushion, additional layer with micro-switches, wireless transmitter and gateway.

3.1. Sensor description

Occupants of commercial office buildings often spend significant time seated at workspaces and at meeting rooms. Therefore, being able to measure the length of time occupants are seated can provide fine-grained information on the use of space, which can be used in demand-driven control of building systems.

The chair sensor is composed of a typical office chair, a cushion with dimensions 42 cm × 4 cm × 5 cm to which an additional layer of foam with a thickness of 1.5 cm was added. The extra layer of foam as depicted in Fig. 4, has 8 low-cost commercially available micro-switches each having a thickness of not more than 5 mm connected in parallel and fixed on it. The output of the parallel connected switches is terminated to a wireless transmitter depicted in Fig. 4 as well, which obtains the state of the connected switches and relays to an online data collection centre via a gateway. To conserve battery power, the wireless transmitter only transmits when a change of state is sensed, i.e., closing of the switch or opening.

3.2. Experimental setup

The performance of the detection system was evaluated using a 25-seat capacity conference room with floor area of 650 ft² (198 m²) depicted in Fig. 5, as test bed. Ventilation to the conference room is supplied via a singular air duct from a constant air volume (CAV) ventilation system, which provides ventilation to all spaces on three floors representing one ventilation zone. For this space, the minimum amount of outdoor air required as recommended by ASHRAE's standard 62-2001 with addendum 62n [20,38] is approximately 165 cfm ((25 × 5) + (0.06 × 650)). The measured air flow rate for the room as shown in Table 2 was approximately 230 cfm, which equates to approximately 9.2 cfm per person for 25 occupants.

Measurement of the CO₂ concentration, airflow rate, air volume as well as the thermal comfort conditions (air temperature, mean radiant temperature (MRT), relative humidity) were as well recorded. The additional measurements were included in order to compare the performance of the designed system with a common readily available occupancy detection systems as well as to get

Table 2
Space measured air flow-rate.

Time	Supply air flow rate (cfm)
7:30AM	233
7:45AM	225
8:00AM	236
8:15AM	223
Average	230



Fig. 5. Test-bed conference room.

a representation of the thermal comfort conditions in the space. In addition, door contact sensors were installed on the room's entrances in order to obtain information on the door states.

3.3. Evaluation of detections systems performance

3.3.1. Location, presence and count properties

As all the sensors were fitted in the same room with each having a unique identification number, information on the location property of occupancy was hence readily available. Results from all 25 installed sensors for a single test-day is depicted in Fig. 6. The conference room on this particular day, the 28th of the month was scheduled to be occupied from 9AM until 4PM as registered in Microsoft's Outlook meeting scheduler. As shown in Fig. 6, presence in the conference room was recorded at about 9:00AM when 4 occupants were registered seated and all occupants can be observed as shown in Fig. 6, to have departed from the space by 4:30PM. These results demonstrate the detection system's ability to provide near real-time information on the presence property of occupancy with negligible network latency.

On the other hand however, results of the CO₂ concentration in the space as depicted in Fig. 7 shows a slower response with

a delay of almost 30 min. Contributory factors attributable to the slow response includes but are not limited to the following: sensors location, environmental factors such as the opening and closing of the doors as well as amount of supply air to the space, which all affect the gas mix rate.

The number of seated occupants depicted in Fig. 6, indicates slight variations between 9:00AM and 11:15AM and 3:30PM and 4:30PM, with the number of seated occupants peaking at 11 and 13 respectively. Between 11:15AM and 3:30PM, the number of seated occupants peaked at 7 and remained constant through the period. The ground-truth value, i.e., the number of seated occupants, was verified and recorded manually at 30 min intervals through the course of the day. As shown in Table 2, the number of seated occupants recorded by the chairs corresponds with the recorded ground-truth data giving an error of 0%.

The number of occupants in the space was also estimated from the measured space CO₂ using the steady state relation provided in [19,38]:

$$\text{No. Occupants} = \left(\frac{SA \times (N - C_i)}{G \times 10^6} \right) \quad (1)$$

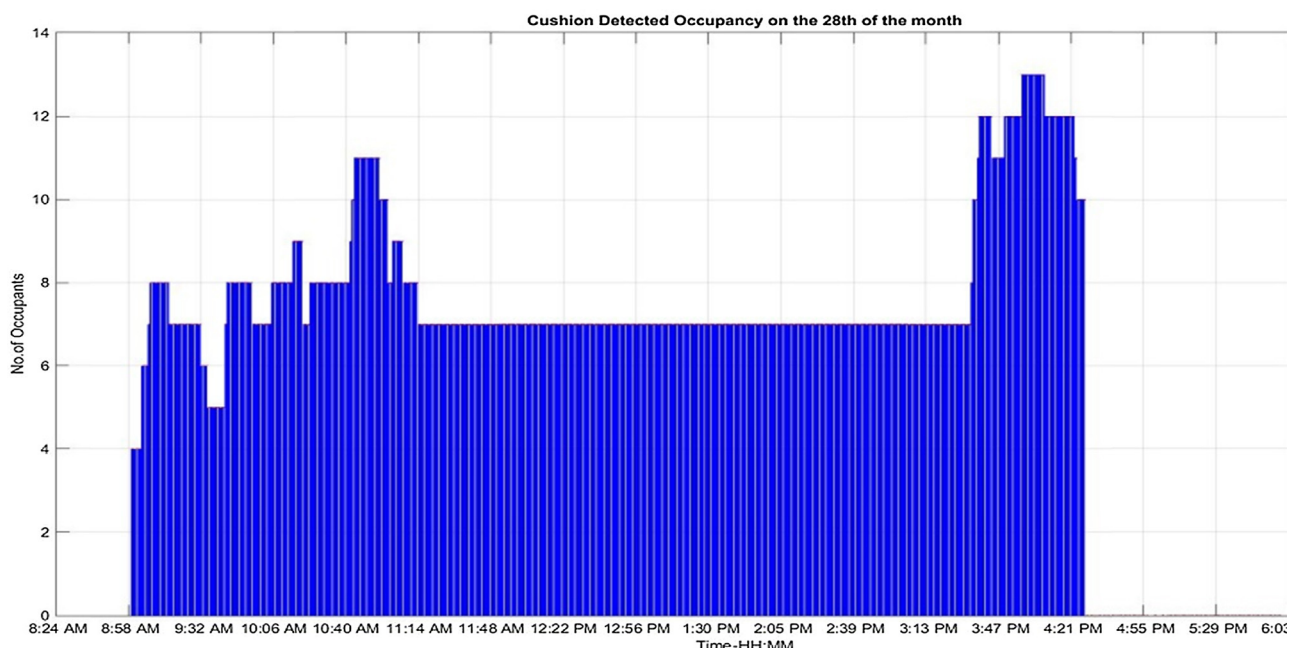


Fig. 6. Chair registered presence in the conference room.

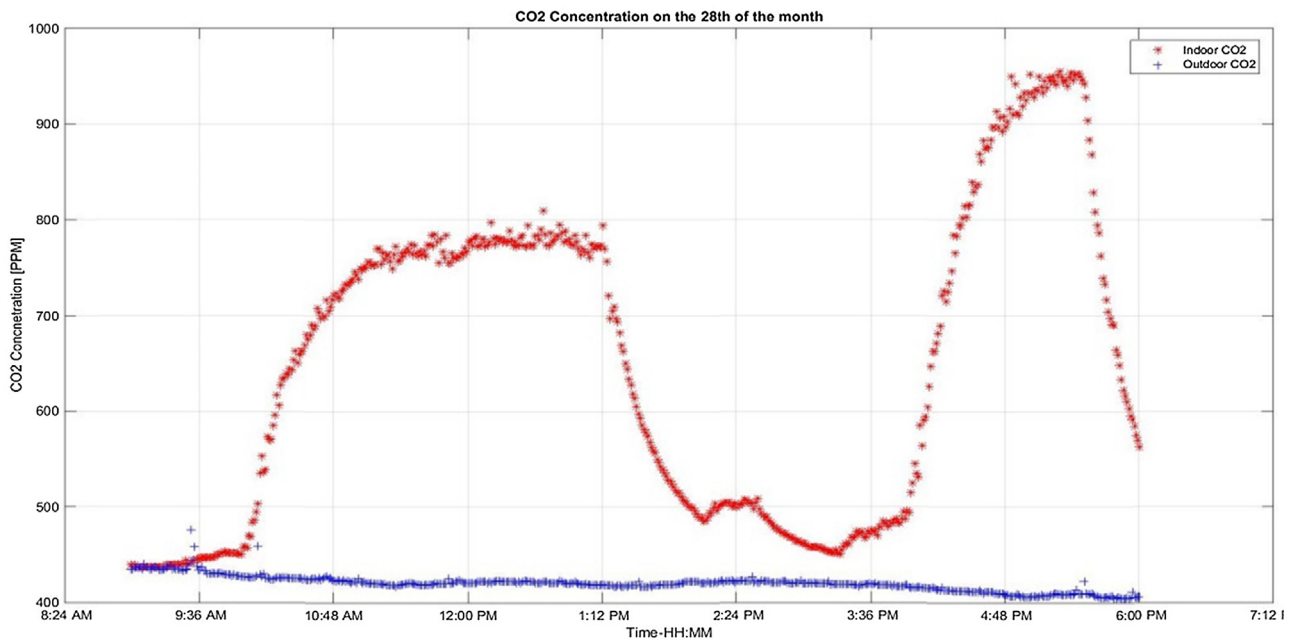


Fig. 7. Space CO₂ concentration measurement.

where N is the space CO₂ concentration at the present time step measured in ppm, SA is the supply air flow rate, C_i is the CO₂ concentration in the supply air measured in ppm, G is the CO₂ generation rate per person measure in cfm.

The estimated value of the number of people in the space on this test day evaluated using the above relation is depicted in Fig. 8. Where, the value of the supply air-flow rate G , was 230 cfm, and the estimated value of the amount of CO₂ generated per person was 0.01 cfm [31].

As can be observed from Fig. 9 and Table 3, the output from the CO₂ occupancy estimates shows some variance with the obtained data from the chair sensors and the ground-truth value. These results further buttresses the drawbacks of CO₂ sensors enumerated in Section 2.2.1.

3.3.2. Energy savings

It is difficult and often impossible in practice as with the case of the test room, to vary the air supply from a constant air volume supply ventilation system without severely affecting ventilation to other building zones supplied by the same ventilation. However, where possible the energy savings in an ideal situation with a variable air ventilation system can be deduced using the relation shown [14]:

$$E_s = (Q_{cav} - Q_{DC}) \times SFP \quad (2)$$

where E_s is the estimated energy saving in kilo-Watt-hour (kWh), Q_{CAV} the daily total outdoor air intake volume of the air handling unit and Q_{DC} the daily outdoor air intake volume of the demand control system. The specific fan power (SFP), which is the power

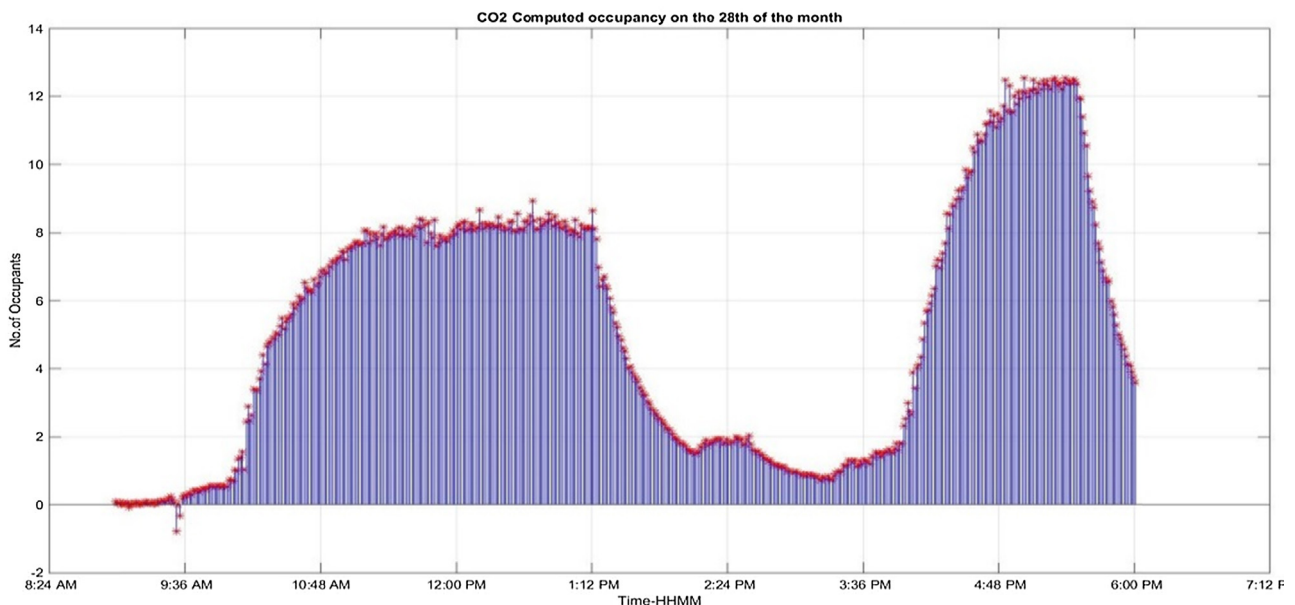


Fig. 8. CO₂ Estimated number of room occupants.

Table 3
Manually recorded ground-truth data.

Time	Ground truth	Cushion sensor recorded	Error (%)	CO ₂ computed	Error (%)
8:30AM	0	0	0	0	0
9:00AM	4	4	0	0	0
9:30AM	7	7	0	0	0
10:00AM	7	7	0	1	86
10:30AM	8	8	0	5	37
11:00AM	8	8	0	7	12
11:30AM	7	7	0	7	0
12:00PM	7	7	0	8	12
12:30PM	7	7	0	8	12
1:00PM	7	7	0	8	12
1:30PM	7	7	0	4	43
2:00PM	7	7	0	2	71
2:30PM	7	7	0	2	71
3:00PM	7	7	0	1	86
3:30PM	7	7	0	1	86
4:00PM	13	13	0	3	77
4:30PM	0	0	0	10	100

efficiency of the supply and exhaust fans of the ventilation unit can as well be deduced as shown in the following equation.

$$Q = \sum_{t=1}^{24} \left(\frac{V_{oz,t}}{1000} \times 3600s \right) \quad (3)$$

where $V_{oz,t}$ is the hour-specific zone outdoor airflow calculated in accordance with equations (6.2.2.1 and 6.2.2.3) of the ASHRAE standard 62.1-2013 [17].

Using the above relation in Eq. (2) and the information provided by the detection system, it can be deduced that the value of E_s if varied dynamically with the number of building occupants would reduce and improve the energy performance of the space. Hence during the period between 10:30AM and 11:30AM depicted in Fig. 6, when the number of occupants dropped from 11 to 7, reducing the supplied ventilation would result in worthwhile reduction in the value of E_s , which would have hitherto remained constant.

4. Discussion

4.1. Practical control application

Initial results from the evaluation of the chair sensors as presented, demonstrates the sensors are a viable, low-cost, reliable alternative occupancy detection system, which can be used in building operations to provide fine-grained occupancy information for the control of building systems. As depicted in Fig. 6, it can be observed that during the early part of the study, between the hours of 9:00AM–11:15AM rapid changes in the number of occupants seated were recorded. The reason for the recorded changes can be attributed to increased door opening and closing action as depicted in Fig. 10. Second, changes in the order of seconds were observed from the evaluated sensors output as depicted in Fig. 11. This changes can be attributed to changes or a swift adjustment in the seated occupants position, which results in rapid opening and closing of the switches.

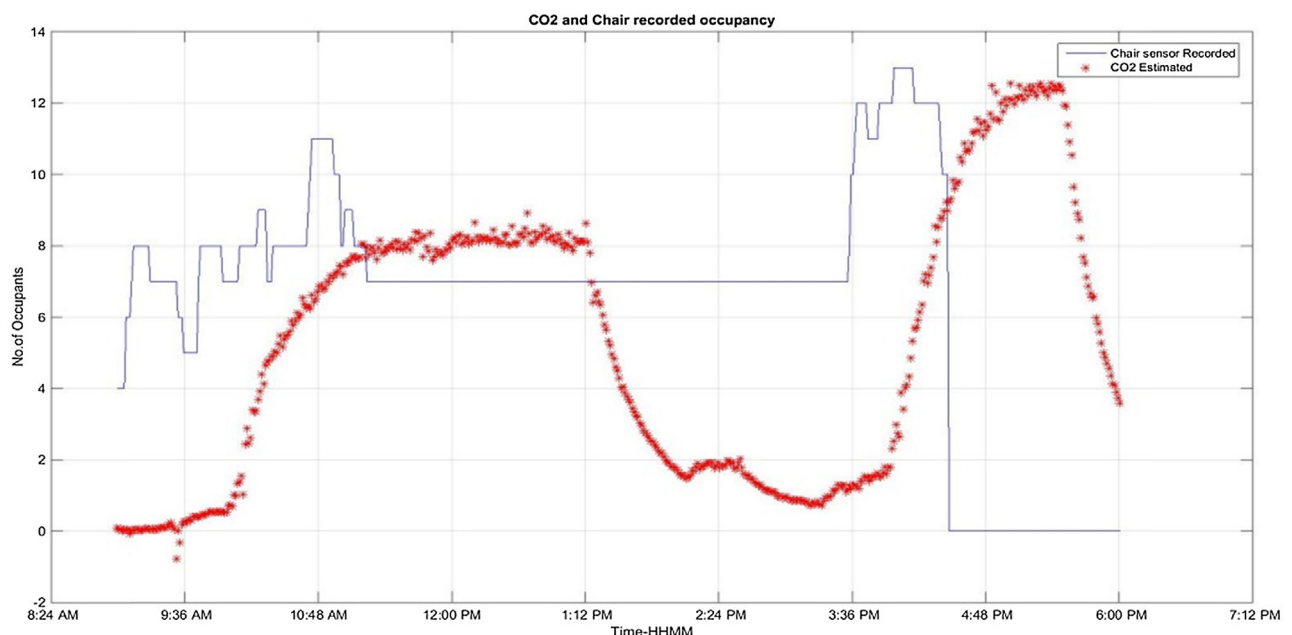


Fig. 9. CO₂ Estimated occupancy and chair recorded.

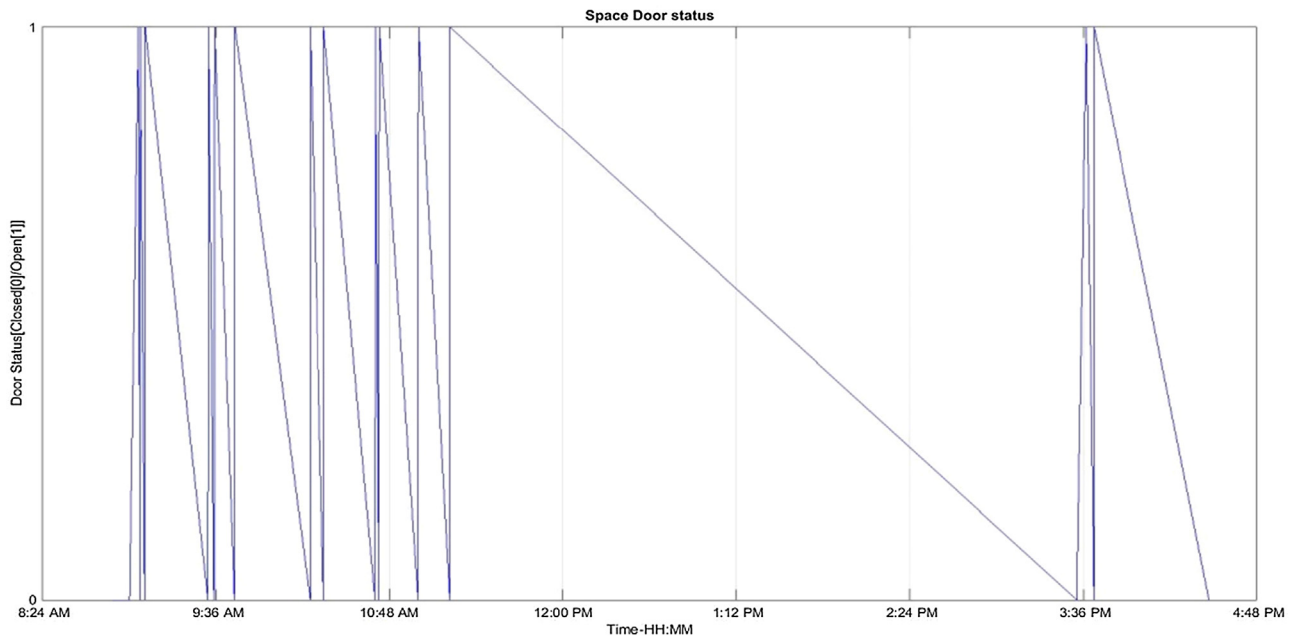


Fig. 10. Door opening and closing actions.

In practical control applications however, such rapid changes could be detrimental to the systems overall performance, this can however be compensated for by a control algorithm. A simplified control algorithm as that depicted in Fig. 12 can be utilized to compensate for rapid changes in occupants seating position. The control algorithm can also be modified for use with fast responding systems such as lighting systems.

The detection system's sensitivity was also evaluated by placing varying weights on the chairs so as to determine the minimum weight that would force the switches into a closed position. This test was necessary as a common drawback of a number of the reviewed detection system was false ON's, i.e., a situation

that causes the detection system to sense presence when objects other than humans are within the sensors vicinity. As depicted in Fig. 13, a closed switch position was only recorded when a direct force of up to 108 kg m/s^2 , which corresponds to a weight of approximately 11 kg, was applied to the contact switches. Using laptop bags weighting less than 11 kg, it was observed that the switches were also forced into a closed position as a result of the increased impact force often present when such bags were suddenly dropped. But as the change in state was also in the order of seconds, the control algorithm depicted in Fig. 13 can as well be used to limit its effect on the overall system's operation.

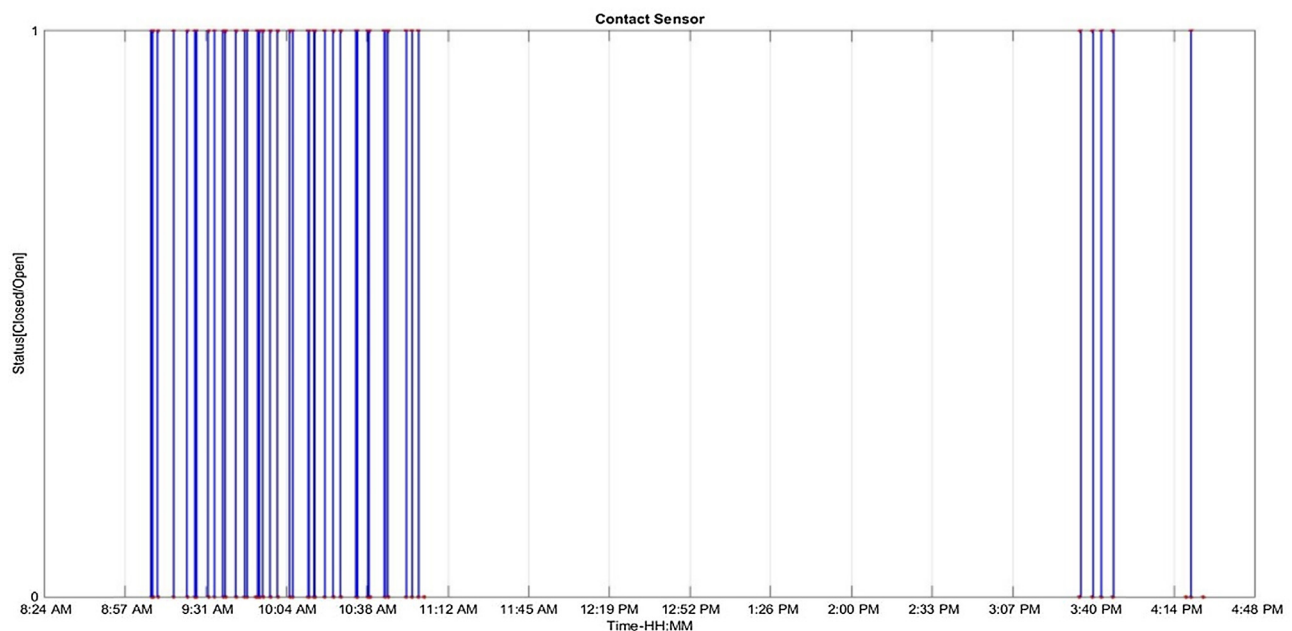


Fig. 11. Observed rapid change in sensor state.

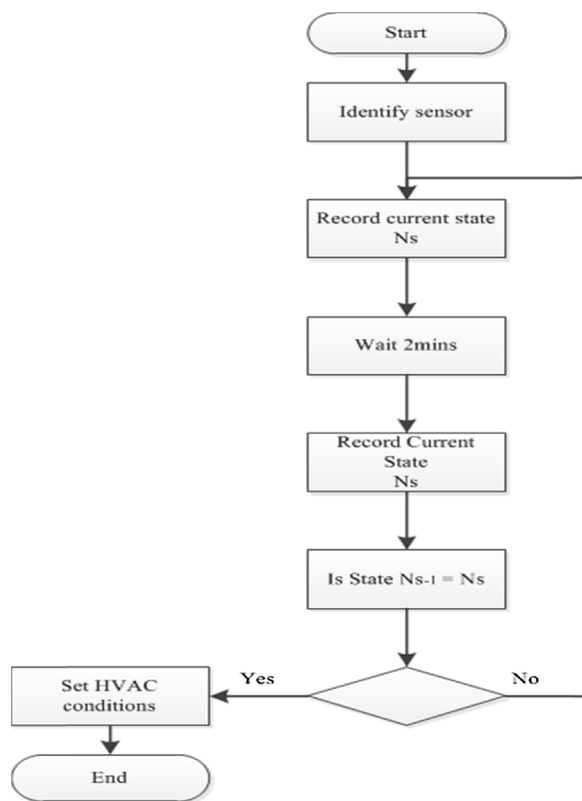


Fig. 12. Flow chart of control algorithm.

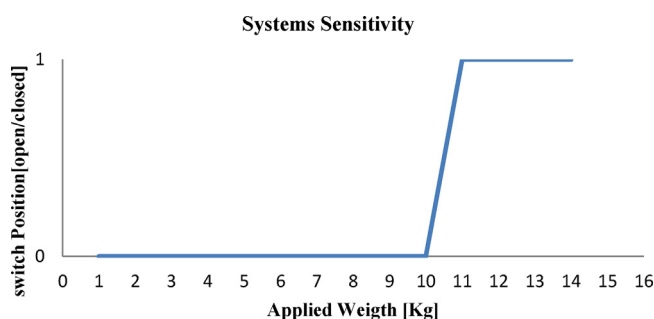


Fig. 13. Detection systems sensitivity.

4.2. Detection system's limitations

A limitation of the system as observed in the course of its evaluation was its inability to detect standing occupants. Building occupants often stand while carrying out certain activities and as no contact is made with the chairs a false read is registered by the sensor. Considering that a significant number of occupants of commercial office buildings often spend ample time seated when at their workspaces, restricting the use of the evaluated detection system to such building occupants would minimise the risks of false off. In addition, the rapid changes in the state of the sensors triggered by occupant's adjustment to their seating position is also a major limitation of the system as discussed earlier. However, introducing a delay as depicted in Fig. 12 to the detection systems circuitry would mitigate against such output being transmitted to the building control systems.

Though the designed system was modular, easy to install and can be easily integrated with existing building energy management systems, some participants were not particularly willing to have such a system attached to their office chairs. A survey of 15

participants revealed only 9 would like to have such a cushion fitted to their work-space, while 6 objected. All surveyed participants however showed positive optimism when asked if they be willing to make use of such a system if it were to be embedded in the office chairs.

5. Conclusion

The utilization of comprehensive fine-grained occupancy information is vital in the efficient application of demand-driven measures in buildings. In this paper, it was shown that obtaining this information for use in building control could oftentimes be challenging as a result of stochastic human behaviour as well as the limitation of available detection tools. To overcome the challenges posed by the latter, chair sensors were introduced and their performance evaluated in the conference room of an office building.

Results from the detection systems evaluation shows that the system is capable of providing fine-grained occupancy information for improving demand-driven control measures in buildings. The experimental set-up also highlighted the advantages of utilizing ventilation systems that can be dynamically varied as opposed to systems that provide constant amount of ventilation for improving overall building energy performance. The detection system was also shown to have some drawbacks, which was also shown to be resolvable through a control algorithm hence not affecting the systems performance. Being only an experimental study, on-going research is currently at an advanced stage to design actual chairs with this embedded system for integration in building control as against the use of the cushions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.enbuild.2015.02.028>.

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